U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-287 820

# Report on FY 1977 Numerical Modeling in Puget Sound

(U.S.) National Oceanic and Atmospheric Administration, Boulder, CO

Jun 78

78092102

PB 287820

NOAA Technical Memorandum ERL MESA-30

# REPORT ON FY 1977 NUMERICAL MODELING IN PUGET SOUND

C. S. Smyth

Marine Ecosystems Analysis Program
Boulder, Colorado
June 1978

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

noaa NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION / Environmental Research Laboratories

NOAA Technical Memorandum ERL MESA-30

# REPORT ON FY 1977 NUMERICAL MODELING IN PUGET SOUND

C. S. Smyth

Pacific Marine Environmental Laboratory
Seattle, Washington

Marine Ecosystems Analysis Program
Boulder, Colorado
June 1978

UNITED STATES
DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Richard A. Frank, Administrator

Environmental Research
Laboratories
Wilmot N. Hess, Director

Report Submitted to
MESA PUGET SOUND PROJECT
MARINE ECOSYSTEMS ANALYSIS PROGRAM
ENVIRONMENTAL RESEARCH LABORATORIES

by

PACIFIC MARINE ENVIRONMENTAL LABORATORY
ENVIRONMENTAL RESEARCH LABORATORIES
SEATTLE, WASHINGTON 98105

This work is the result of research sponsored by the Environmental Protection Agency and administered by the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration.

The Environmental Research Laboratories do not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to the Environmental Research Laboratories or to this publication furnished by the Environmental Research Laboratories in any advertising or sales promotion which would indicate or imply that the Environmental Research Laboratories approve, recommend, or endorse any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this Environmental Research Laboratories publication.

ACKNOWLEDGEMENTS

The entire job of coding and testing the Puget Sound trajectory model was accomplished almost single-handedly by Gary D. Kimura. The work was done correctly, on schedule, and under trying circumstances.

CONTENTS


Acknowledgements..... iii
List of figures..... vi
Abstract..... 1
1. Introduction..... 1
2. General dispersion model: concept..... 3
3. General dispersion model: realization..... 5
3.1. Surface current interpolation..... 6
3.1.1. Introduction..... 6
3.1.2. The algorithms..... 7
3.1.2.1. Nearest station assignment..... 7
3.1.2.2. Distance-weighted combinations..... 8
3.1.2.3. Preassignment..... 9
3.1.3. Performance..... 10
3.1.4. Summary..... 11
3.2. Regional meteorological model..... 13
3.2.1. Introduction..... 13
3.2.2. Mathematical basis..... 13
3.2.3. Results..... 15
3.2.4. Summary..... 25
3.3. A simple trajectory model for Puget Sound..... 26
3.3.1. Introduction..... 26
3.3.2. Brief mathematical description..... 26
3.3.3. Data sources..... 29
3.3.3.1. Surface currents..... 29
3.3.3.2. Surface winds..... 29
3.3.3.3. Geometry..... 29
3.3.4. User interface..... 30
3.3.5. Comparison of results with observations..... 30
4. Summary..... 30
5. References..... 32
6. Appendix I. Trajectory model users' guide..... 33
7. Appendix II. Trajectory model program listing..... *
8. Appendix III. Regional meteorological model listing.. *


* Appendices II and III are on microfiche attached to inside back cover.



Preceding page blank

## FIGURES


Figure1. Western Washington study area..... 2
Figure 2. East wind case: Observations..... 16
Figure 3. East wind case: Model results..... 18
Figure 4. Soutwest wind case: Observations..... 20
Figure 5. Southwest wind case: Model results (h=1800 m). 21
Figure 6. Southwest wind case: Model results (h=900 m).. 22
Figure 7. Northwest wind case: Observations..... 24
Figure 8. Northwest wind case: Model results..... 25
Figure I-1. Trajectory model status report..... 43
Figure I-2. Current table report..... 44
Figure I-3. Current vector diagram..... 45
Figure I-4. Spill trajectory plots..... 46
Figure I-5. Superimposed trajectory plot..... 47

# REPORT ON FY 1977 NUMERICAL MODELING IN PUGET SOUND

C.S. Smyth

ABSTRACT. A simple single-phase pollutant trajectory model and two basic components, a method for computing surface currents, and a method for computing surface winds were developed for the Puget Sound region. The model simulates the motion of a number of discrete floating elements under the influence of surface currents, surface winds, and parameterized diffusion. The floating elements may be introduced from several (possibly moving) sources. The computed paths of these elements approximate the paths that would be followed by a single-phase floating pollutant. The model is operational and may be accessed via voice-grade telephone lines.

## 1. INTRODUCTION.

The research and development effort described in this report was aimed toward a single goal: production of an operational method for predicting the motion of floating pollutant substances on the inland marine waters of western Washington State (Figure 1) prior to the end of FY 1977. In order to reach this goal, a number of design decisions and compromises were necessary. This report documents that design and its products.

In order to compute the motion of a floating substance one must allow for each of the processes that cause motion and change in components of that substance. Because a floating substance lies at the interface separating ocean and atmosphere, and is in contact with each, it is natural to suppose that the physical motion of the sea and the air may each be important in determining the transport of the substance. In fact, only two other processes were considered in this work: generative processes that create more substance, and traps that cause motion of the substance to cease.

FIGURE 1. Western Washington Study Area.

A major simplification was made in considering that the substance be homogeneous, that is, of a single physical-chemical phase.

The motion of the floating single-phase substance was described mathematically in terms of given motion of the air and water near the air-water interface, and a computer implementation of a solution to those equations was designed,

coded, tested and made operational on a DEC PDP-11/55 computer at Pacific Marine Environmental Laboratory. This program is referred to as the Puget Sound Trajectory Model (PSTM).

The PSTM is conceptually simple and it is constructed in a modular fashion, so that one might easily change or enhance the mathematical basis without modifying what the user sees at a timesharing terminal. The portion of the model that interacts with the user is referred to as the "operator interface". A great deal of effort was devoted to the operator interface because I feel that the ease with which the model may be made to respond to desires of the user will determine the ultimate usefulness of this work in dealing with real problems.

An important factor in developing confidence in the model is an understanding of what facts are being manipulated and how those manipulations are carried out. The remainder of this report describes in detail the overall strategy; the tactical means by which the surface currents; surface winds and turbulence were handled; data sources; some implementation details; a user's guide for the PSTM; and Fortran program listings.

## 2. GENERAL DISPERSION MODEL: CONCEPT.

A complete surface dispersion model should be able to handle a number of component phases, a number of sources, a number of sinks, interphase reactions, special boundary conditions (absorbing, partially absorbing, time-dependent, etc.) at a spatial resolution fine enough to resolve all separate sources and sinks, and all geographic features of interest. It should be possible to compute concentrations for each substance phase at any model time, and it should be possible to run the model in "reverse time" to estimate the earlier distribution patterns that may have led to a present state. A basic principle that may be used to obtain all these desired capabilities is <u>conservation of mass.</u>

A fairly general mass conservation statement for a constant-thickness multi-phase floating substance (where floating implies that there can be no motion normal to the air-water interface) can be expressed in an Eulerian reference frame as the system of K equations

$$C^k_t = -(u' C^k_x + v' C^k_y) + ((D^k_{xx} C^k_x)_x + (D^k_{yy} C^k_y)_y) + R^k \qquad (1)$$

$$(k=1,2,3,\ldots,K)$$

where the superscript k refers to the k-th component phase; of the substance, $D_{xx}$ and $D_{yy}$ are the xx and yy components of an eddy diffusion tensor appropriate (as determined by experiment or other empirical means) for the k-th phase, the remaining t, x, and y subscripts denoting partial differentiation with respect to the time, east and north coordinates, respectively; C is a concentration, u and v are east and north surface current components ("corrected" for surface wind effect, hence the primes) and R is a local generation and phase interaction term. Note that this is a phenomenologically oriented model because of the parametric treatment of turbulent diffusion and allowing the surface wind to be effective through a "correction" mechanism. Both are reasonable and accepted simplifications but they are good candidates for revision in further development to improve the physical basis of the model.

The lefthand side of (1) represents the time rate of change in concentration of phase k at a particular point in space. Given K initial values of $C^k$ at each point, (1) could be numerically integrated over time to give the desired $C^k(x,y)$.

This would be expensive computationally because the derivatives of $C^k$ must be computed numerically to approximate the first two terms on the lefthand side of (1)(representing advective and diffusive effects, respectively) propagate outward from any point to the boundaries of the modeled region after a sufficient number of time steps. One must compute $C^k(x,y)$ for all (x,y) in the region studied even if $C^k(x,y)$ is needed at only one point. A second difficulty is that the numerical computation of spatial derivatives results in a "numerical diffusion" effect in the advective term. A point source ($C^k(x,y,t)$ nonzero for only one (x,y)) cannot have its derivatives represented properly in the advective (first) term of the righthand side of (1). A small nonzero component of velocity will cause a transfer of part-but not all- of the concentration to an adjacent point in a finite difference mesh. Thereafter the original "point" will occupy at least two points with a further spreading occurring with each advective step. Finally, expert attention and analysis are required for setting up the boundary conditions, selecting a time step, and evaluating model results for numerical instabilities.

For reasons of modularity, design simplicity, and computational efficiency, I have chosen to employ a Lagrangian approach to solution of (1). A separate but crucial consideration is the generation of the surface current velocity components, u and v. Once again, Eulerian conservation of mass and conservation of momentum (Newton's Second Law) principles could be combined with suitable initial and boundary conditions to yield a solution over the entire space-time region of interest. This approach was dismissed because of the enormous size and complexity of a finite difference grid or finite element mesh able to resolve the contorted three-dimensional geometry of Puget Sound.

Instead, the available data from the NOS Tidal Current Tables for North America and Asis, 1976 (NOS, 1975) were used as a data base for a current interpolation procedure. Several interpolation procedures were examined; they all make use of the fact that the current velocity is known to be zero on land; some make use of a condition that water cannot flow through land boundaries (not necessarily realistic in three-dimensional flow); and there are varying degrees of sophistication in the manner of combination of values from various stations. One should remember that none of the available predicted currents can be more accurate than the NOS predictions themselves, and are undoubtedly less accurate away from the NOS station locations. The unknown quality of the surface currents is a major shortcoming of the model in its present state of development.

In the case of surface winds, there are too few measurement stations to be able to employ any simple interpolation scheme to compute local winds. A more complex method, using physical principles to guide the interpolation process, is embodied in the regional meteorological model developed by Overland et al (Overland, et al, 1978). This finite difference model takes a single initial specification of atmospheric conditions for the region as a whole and inflow boundary conditions and, when run to quasi-steady state, yields smoothed local winds at the surface after accounting for the effects of terrain, local heating/cooling, and atmospheric stability. The results of this model could be (but have not yet been) assembled into a database accessible to the PSTM.

## 3. GENERAL DISPERSION MODEL: REALIZATIONS.

The actual model implemented does not have some important capabilities expected of a general dispersion model: only a single component phase is allowed for the floating substance, only point sources are possible, no means is available to compute local point densities to estimate C' (or C as only a single phase will be considered). In fact, the model's main

function is to compute the paths of representative particles of floating substance in a Lagrangian reference frame. Therefore it is really a trajectory model rather than a more complete dispersion model.

The following sections detail the development of procedures to compute surface currents and surface winds from the available data, and the actual design of the Puget Sound Trajectory Model.

## 3.1. Surface Current Interpolation.

### 3.1.1. Introduction.

Surface current interpolation is the process used to compute current velocities at points inside the convex hull of points where current velocities are known from measurement or prediction. Because the flow may be three-dimensional, there are very few constraints on the horizontal component of the the surface currents, given only velocities at a few points. The best procedure can only satisfy experience and physical intuition.

Given a predicate

$$\underline{\text{water}}(\underline{\text{lat}},\underline{\text{lon}}) = \text{the earth's surface at geographic position } \underline{\text{lat}},\underline{\text{lon}} \text{ is covered by water} \qquad (2)$$

and a collection of functions $u_j(t)$ and $v_j(t)$ that transform time (t) into horizontal surface velocity components in the easterly (u) and northerly (v) directions at geographic positions $\underline{\text{lat}}_j,\underline{\text{lon}}_j$ where $j=1,2,3,\ldots,J$, what two procedures can be constructed to yield $\hat{u}(\underline{\text{lat}},\underline{\text{lon}},t)$ and $\hat{v}(\underline{\text{lat}},\underline{\text{lon}},t)$ for some open rectangular prism S such that $\underline{\text{lat}}_1<\underline{\text{lat}}<\underline{\text{lat}}_2$, $\underline{\text{lon}}_1<\underline{\text{lon}}<\underline{\text{lon}}_2$, and $t_1<t<t_2$ for all $\underline{\text{lat}}$, $\underline{\text{lon}}$, t in S and

$$\begin{aligned} \hat{u}(\underline{\text{lat}},\underline{\text{lon}},t) &= u_j(\underline{\text{lat}}_j,\underline{\text{lon}}_j,t) \\ &\quad \text{iff } \underline{\text{lat}} = \underline{\text{lat}}_j \text{ and } \underline{\text{lon}} = \underline{\text{lon}}_j \\ \hat{v}(\underline{\text{lat}},\underline{\text{lon}},t) &= v_j(\underline{\text{lat}}_j,\underline{\text{lon}}_j,t) \\ &\quad \text{iff } \underline{\text{lat}} = \underline{\text{lat}}_j \text{ and } \underline{\text{lon}} = \underline{\text{lon}}_j \end{aligned} \qquad (3)$$

and

$$\underline{\text{not}}(\underline{\text{water}}(\underline{\text{lat}},\underline{\text{lon}})) \text{ implies } \hat{u}(\underline{\text{lat}},\underline{\text{lon}},t)=\hat{v}(\underline{\text{lat}},\underline{\text{lon}},t)=0 \text{ for all t?}$$

Assume for the moment that the lat, lon rectangle is a subset of the convex hull of the points $lat_j$, $lon_j$, j=1,2,3,...,J. This is then a general interpolation problem complicated by the predicate clause. I will describe successively more complicated forms for $\hat{u}$ and $\hat{v}$ and discuss their relative merits from both an end use and computational point of view.

3.1.2. The Algorithms.

I have grouped the algorithms which may be employed to compute $\hat{u}$ and $\hat{v}$ according to whether or not a single $u_j$, $v_j$ pair is used.

3.1.2.1. Nearest Station Assignment. In nearest station assignment

$$\begin{aligned} \hat{u}(lat,lon,t) &= u_j(lat_j,lon_j,t) \text{ if } water(lat,lon) \\ &= 0 \text{ otherwise} \\ \hat{v}(lat,lon,t) &= v_j(lat_j,lon_j,t) \text{ if } water(lat,lon) \\ &= 0 \text{ otherwise} \end{aligned} \quad (4)$$

where j is chosen to minimize a metric $d(lat,lon,lat_j,lon_j)$: the "nearest" station (j) is selected. A tie-breaking rule must be employed if several points $(lat_j,lon_j)$ may have the same d value for a given (lat, lon). The tie-breaking rule is usually implicit in the minimization process and often depends on the ordering of the $(lat_j, lon_j)$ with respect to j. Therefore different permutations of the data base may yield different interpolated results. A second characteristic of nearest station assignment is that the resultant current velocity components are discontinuous at the boundaries of regions closest to different $(lat_j,lon_j)$.

An important feature of the nearest station assignment process is that one may a priori assign every resolvable (lat, lon) point in S to a j-index, since the metric is time-independent. This is called "preassignment" and can greatly reduce computational effort in individual current calculations. Preassignment is described in a later section.

3.1.2.1.1. Euclidean Metric. The most obvious metric is the Euclidean distance which for geographic coordinates on a flat earth approximation may be written approximately as

$$d_E = ((lat-lat_j)^2+((lon-lon_j)/\cos(lat))^2)^{\frac{1}{2}}. \quad (5)$$

This metric is easy to compute but suffers from several definite drawbacks. The most serious is that the nearest station by $d_E$ may not be the station most closely related by the physics of fluid flow. For example, there may be two isolated channels (such as the terminal ends of Hood Canal and Carr Inlet) that are separated by land where some points in one will be nearer a station ($\underline{lat}_j$, $\underline{lon}_j$ point) in the other channel than in its own. In such a case, the interpolated current velocity will be meaningless. Unfortunately, the method does not give any indication of trouble in such a case.

3.1.2.1.2. Water Path Metric. Another metric that may be used is the length of the shortest path from one point ($\underline{lat}$, $\underline{lon}$) to another ($\underline{lat}_j$, $\underline{lon}_j$), under the condition that at no point along the path ($\underline{lat}_p$, $\underline{lon}_p$) can water($\underline{lat}_p$,$\underline{lon}_p$) be false. This water path distance measure, $d_w$, satisfies all conditions necessary to qualify as a metric (Maunder, 1970). It also yields intuitively appealling dissections of the water region of S, assigning an open polygon (s) to each of the J stations in the current data base. Calculation of $d_w$ can only be carried out by a search procedure in which all paths from the point ($\underline{lat}$, $\underline{lon}$) to the point ($\underline{lat}_j$, $\underline{lon}_j$) must be considered. Fortunately, there exist heuristic search procedures such as the optimal state space search (Nilsson, 1971) that waste little effort examining "unlikely shortest paths" until all better candidates have been shown to be failures. The computational effort (at least a number of $d_E$ calculations that is proportional to $d_E(\underline{lat},\underline{lon},\underline{lat}_j,\underline{lon}_j)$ will be made) and storage requirements are variable, however, and a search may terminate without finding any path if insufficient storage is provided. In summary, $d_w$ is intuitively appealing but not suitable for interactive use due to the computational effort required and the potentially large storage requirement. This metric might best be applied in preassigning stations to regions.

In the vicinity of ($\underline{lat}_j$,$\underline{lon}_j$) points (without intervening non-water areas) $d_E = d_w$, so the superiority of the $d_w$ metric for assignment is only evident at a distance from current measurement stations.

3.1.2.2. Distance-Weighted Combinations. In order to smooth the transition from the region nearest ($\underline{lat}_j$, $\underline{lon}_j$) from one j to another it is possible to combine $(\hat{U}, \hat{V})^j$ pairs obtained by assignment so that the $\hat{U}$ and $\hat{V}$ are continuous.

3.1.2.2.1. Linear Combinations. The simplest combination is a linear one. Let $j_m$ be the subscript of the station m-th nearest (by some metric d) point (lat, lon). Then let

$$d_m = d(\underline{lat},\underline{lon},\underline{lat}_{j_m},\underline{lon}_{j_m})$$

then

$$w_q = (d_1+d_2+\ldots+d_{q-1}+d_{q+1}+\ldots+d_n)/(d_1+d_2+\ldots+d_n) \quad (6)$$

and

$$\begin{aligned} 0 &= w_1 u(\underline{lat}_{j_1},\underline{lon}_{j_1},t) \\ &\quad +w_2 u(\underline{lat}_{j_2},\underline{lon}_{j_2},t) \\ &\quad \vdots \\ &\quad +w_n u(\underline{lat}_{j_n},\underline{lon}_{j_n},t) \\ 0 &= w_1 v(\underline{lat}_{j_1},\underline{lon}_{j_1},t) \\ &\quad +w_2 v(\underline{lat}_{j_2},\underline{lon}_{j_2},t) \\ &\quad \vdots \\ &\quad +w_n v(\underline{lat}_{j_n},\underline{lon}_{j_n},t) \end{aligned} \quad (7)$$

for the n-station distance-weighted average. Since the boundary between regions always separates two areas, n=2 is often a good choice.

3.1.2.2.2. Nonlinear Combinations. It is clear that the weights, w, in (7) need not be linear in d. In fact it may be desirable to use $d^2$ in (6). The use of nonlinear weights can be generalized to interpolating functions defined either within the station ($j_m$) with which they are associated or throughout the lat, lon rectangle.

A special case occurs near land-water boundaries where at least esthetically one would like the component of the surface current normal to the shoreline to nearly vanish at the shoreline. This can be accomplished by treating the entire shoreline as a station with special topological properties. Calculation of d for land becomes a search for the nearest land. Equations (3) automaticallyyield a vanishing current at the land-water boundary. Only a suitable set of weights $w_q$ need be defined. In practice, $W_q$ based on $d^2$ yield a pleasing cross-channel profile.

3.1.2.3. Preassignment. As noted, it is possible to assign every point in S to one particular station j before any

interpolations are performed. It is also possible to precompute the weights in (6). This preassignment process makes it practical to apply complicated interpolation procedures during an actual trajectory model run because the most time-consuming portion of the calculation will have already been performed. As a practical matter, the points assigned to individual stations form dense sets surrounding the stations, and the boundary of such a set is usually a polygon. Therefore, only the polygon need be stored.

### 3.1.3. Performance.

The performance of different interpolation methods can be described in terms of how well the interpolated values approximate actual values, how long it takes to compute an individual value, and how much memory is required for the calculation.

Numerical experiments were performed using six different interpolation algorithms and the NOS Tidal Current Tables stations (NOS, 1975). The algorithms were:

1. nearest station assignment by Euclidean metric

2. linear combination, with n=2, and one station restricted to be the land-water boundary, using the Euclidean metric

3. linear combination, with n=3, and excluding the land-water boundary, using the Euclidean metric

4. linear combination, with n=4, and one station restricted to be the land-water boundary, using the Euclidean metric

5. same as 3 but using water-path metric

6. same as 4 but using water-path metric.

The results of these experiments are presented in Table 1.

| ALGORITHM | BOUNDARY | MEAN ERROR | STD DEV | MEAN TIME | STD DEV |
|---|---|---|---|---|---|
| 1 | NO | 0.00 | ---- | 0.31 | 0.02 |
| 2 | YES | 0.02 | 0.00 | 0.45 | 0.02 |
| 3 | NO | 0.06 | 0.02 | 1.18 | 0.03 |
| 4 | YES | 0.06 | 0.02 | 1.36 | 0.03 |
| 5 | NO | 0.08 | 0.08 | 8.27 | 1.22 |
| 6 | YES | 0.08 | 0.08 | 8.63 | 1.20 |

TABLE 1. Surface Current Interpolation Performance Data.

The "BOUNDARY" column refers to whether or not the land-water boundary was used as a station, the "MEAN ERROR" column is the average error in computing current velocity components at 100 randomly selected pairs of geographic coordinates in Puget Sound, the "STD DEV" column lists the standard deviation of the same interpolated coordinates, the "MEAN TIME" column gives the time in milliseconds of real time required for the computation on a quiet system, and the right-hand "STD DEV" column gives the standard deviation for the time data. The "correct" current velocity components were computed by algorithm 1 (hence no error or standard deviation). Therefore, these data (Table 1) do not represent a very good estimate of the various algorithms' abilities in predicting actual surface currents. Rather, Table 1 presents the differences in the current velocity components that they do compute.

The key item to notice is the great increase in time involved for all algorithms in comparison with 1, and the relatively small difference in the current predictions (less than 0.1 knot on the average). This suggests that the approximately twenty-fold increase in effort (or decrease in model operating speed) observed in using algorithm 6 is hardly warranted by any improvement in surface current interpolation over nearest station assignment. One must be careful not to forget that most of the serious errors can be expected in areas far from any stations in the interpolation data base.

### 3.1.4. Summary.

Although one might expect nearest station assignment by Euclidean metric to be easily improved upon, none of the alternative algorithms studied yielded significantly different resuts in numerical experiments. It is not reasonable to expect any method to really yield accurate current velocities at points far from any stations. The distance-by-water-path metric is intuitively appealing but is not practical for the purposes of this model until preassignment is implemented.

Ultimately one might expect that either

1. fully instrumenting the area of interest with telemetering current meters (and additional data useful in estimating pollutant motion such as temperature sensors and sensors for the pollutant itself), or

2. developing a numerical model based on the physics of fluid flow to compute all required parameters given some initial and boundary conditions

would become the most economical way to proceed. It may turn out that for some geophysical problems the best instrument for modeling a process is the real world itself. The contribution of modeling then becomes fully scientific: it lets alternative realities be explored so that the inner workings can be explained, and these explanations can then be tested against reality.

## 3.2. Regional Meteorological Model.

### 3.2.1. Introduction.

The following is a brief review of the Regional Meteorological Model documented fully in a PMEL Technical Report (Overland, et al, 1978). This model infers local winds and small scale spatial variations in wind fields from the large scale flow pattern for locations where long term direct obervations are not practical. The model is an adaptation of a model proposed by Lavoie (1972,1974) which consists of fairly general conservation statements for mass, momentum, and heat. Lavoie treats the planetary boundary layer (PBL), typically 0.5 to 2 km deep, as a one-layer, vertically integrated primitive equation model. The model solves for the two components of horizonal velocity, boundary layer height, and potential temperature throughout a limited region. Large scale geostrophic wind, surface elevation, temperature, and the stability of the air in the layer above the PBL are specified at the inflow boundaries. The local reponse is calculated by specifying smooth initial values of wind, temperature, and PBL height and then time stepping the equations of continuity, momentum, and heat conservation until an equilibrium state is obtained. The system is free to estimate mesoscale wind variations caused by contrasts in heating and roughness of land and water, modification of the down wind environment by advection and channeling by topography. The equilibrium state is considered to give the local winds which occur in conjunction with the given large scale pressure pattern. Since the model consists of only one layer, processes which depend upon vertical structure cannot be directly resolved; however, the model is well suited to estimating wind pattern in mountainous regions with strong orographic control.

### 3.2.2. Mathematical Basis.

The atmosphere is represented by four layers, defined by changes in the lapse rate of potential temperature. The layer in contact with the surface is a constant stress or Prandtl layer, assumed to be represented by a logarithmic velocity modified by air stability. The upper limit of this layer is taken to be 50 m. Above the constant stress layer is the planetary boundary layer (PBL) represented by vertically integrated values of potential temperature, capped by a density discontinuity (the transition layer) that parameterizes the restoring force of an inversion layer of stable air above the PBL. The inversion layer is assumed to

have internally adjusted to changes in the PBL height so that the influence of the surface boundary is not felt in the free layer above the top of the inversion. The model specifies four dependent variables: The PBL height, h, identified with the inversion base in unstable or neutral stratification; the PBL potential temperature, $\theta$; and the two components of integrated wind velocity within the PBL, (u,v). The governing equations for conservation of mass, momentum and heat result from vertically integrating the primitive equations for the PBL, treating the lower atmosphere as a Boussinesq system. Interactions with the surface layer and upper atmosphere are parameterized. The resulting equations reduce to:

$$E = h_t + uH_x + vH_y, \tag{8}$$

$$(Hu)_t + (Hu^2)_x + (Huv)_y - Hfv = -HF_x + \frac{gH\theta'}{\theta_0} h_x + \frac{gH^2}{2\theta_0} \theta_x + Eu^+ - C_D |u| u, \tag{9}$$

$$(Hv)_t + (Hv^2)_y + (Huv)_x + Hfu = -HF_y + \frac{gH\theta'}{\theta_0} h_y + \frac{gH^2}{2\theta_0} \theta_y + Ev^+ - C_D |v| v,$$

$$(H\theta)_t + (Hu\theta)_x + (Hv\theta)_y = E\theta^+ - C_H (u^2+v^2)^{\frac{1}{2}} (\theta - \theta_s). \tag{10}$$

The left side of the mass conservation equation (8) represents the recruitment of mass into the PBL through entrainment of the overlying stable fluid, E. The height of the top of the PBL above sea level is h and H is the local PBL thickness. In the momentum equations (9), f is the Coriolis parameter; g, gravity; $\theta_0$, a reference temperature; $(u^+, v^+)$, the velocity components at the base of the inversion layer; and $C_D$ a surface drag coefficient. The temperature increase in the transition zone between the top of the PBL and the inversion layer is $\theta'$. The air stability associated with the inversion is thus modeled as a jump condition in density. $F_x$ and $F_y$ represent the pressure gradient forces in the east and north directions associated with the background large scale flow, while the next two terms represent pressure gradients induced by the local variations in PBL height and temperature. In the absence of mesoscale variation, (9) reduces to a geostrophic balance modified by surface drag. The right hand side of the heat equation (10) indicates that the PBL can be warmed by entrainment at the top of the PBL ($\theta^+$ being the temperature at the base of the inversion) or by surface heating proportional to difference between the PBL air temperature and surface temperature, $\theta_s$. Remaining t, x, and y subscripts indicate partial differentiation with respect to the time, easterly, and northerly coordinates of a rectangular coordinate system on a flat earth approximation.

The wind velocity components, u and v, are an average for the entire PBL. Since almost all wind shear is confined to the Prandtl layer, the model wind can be taken as nearly equal to

the wind at 50 m elevation. At this level, the wind speed is approximately 20% greater than the wind measured at the normal anemometer height of 10 m. Corrected for height in this manner, the model winds should correspond to high quality 10-minute-averaged anemometer winds which are not unduly influenced by surface features smaller than the mesh length of the model.

### 3.2.3. Results.

Three generalized meteorological flow conditions were simulated for the Puget Sound System, corresponding to typical summer and winter regimes. In the summer months, anticyclonic flow around a well-developed semi-permanent high pressure cell to the west of the region causes prevailing northwest winds offshore along the western coasts of Washington and Vancouver Island. Midwinter is characterized by a series of cyclonic storms with strong winds from the southwest carrying warm moist air inland over Western Washington. An important winter case, at least on a frequency basis, is the lull between storms with high pressure much of the time to the east of the region giving easterly winds along the Strait of Juan de Fuca and relatively light winds elsewhere.

Two basic regimes describe the general weather characteristics of December in Western Washington. A succession of frontal passages from the west, varying in number and intensity, dominates the flow patterns providing strong winds from the southwest. Between storms, high pressure builds up near the area, often in the continental interior, bringing clear skies and relatively low winds lasting for several days to a week or more. The fall and winter of 1976 were unusual in that a persistently recurring ridge of high pressure over the northeastern Pacific at 500 mb, frequently extending almost to the pole, allowed only an occasional weakened frontal passage through the area. Surface high pressure associated with the 500 mb pattern, but displaced eastward over the continent, dominated in the Puget Sound Basin. A good example of this situation is 0000 GMT on December 1, 1976. For several days prior to and succeeding this time, high pressure prevailed over southeastern British Columbia, extending south over the interior plateau. In the absence of topography, widely spaced isobars would suggest a week flow outward from the high pressure center westward over the area. However, the local wind as shown in Figure 2 reveals a complex pattern with easterly wind at the coast and calm or light northerly winds in the Puget Sound. A very interesting feature is seen in the Strait of Juan de Fuca. In sharp contrast to the weak and variable winds elsewhere on the inland waters, there is a strong flow out the Strait, reaching 20 knots at Cape Flattery.

FIGURE 2. East Wind Case: Observations.

Associated with these low level wind vectors are temperature soundings over the area revealing a strongly stratified regime throughout the planetary boundary layer. Stability restricts the flow to regions below the mountain tops where the air can be accelerated down-pressure-gradient west through the Strait of Juan de Fuca and west through the Cowlitz Valley south of the Olympic Mountains (Figure 1). The winds can be explained as stronger in the Strait than along the southern Washington

coast because the down-gradient acceleration is uninhibited by surface friction. Another curious feature is that the winds in Puget Sound proper flow south in the opposite direction to an inferred surface geostrophic wind. Figure 3 shows the wind pattern generated by the model which corresponds to the December 1 case. While the boundary layer is not well mixed as assumed in section 3.2.2., the forced channeling for the east wind was simulated by assuming a very shallow PBL in the model capped by very strong stability.

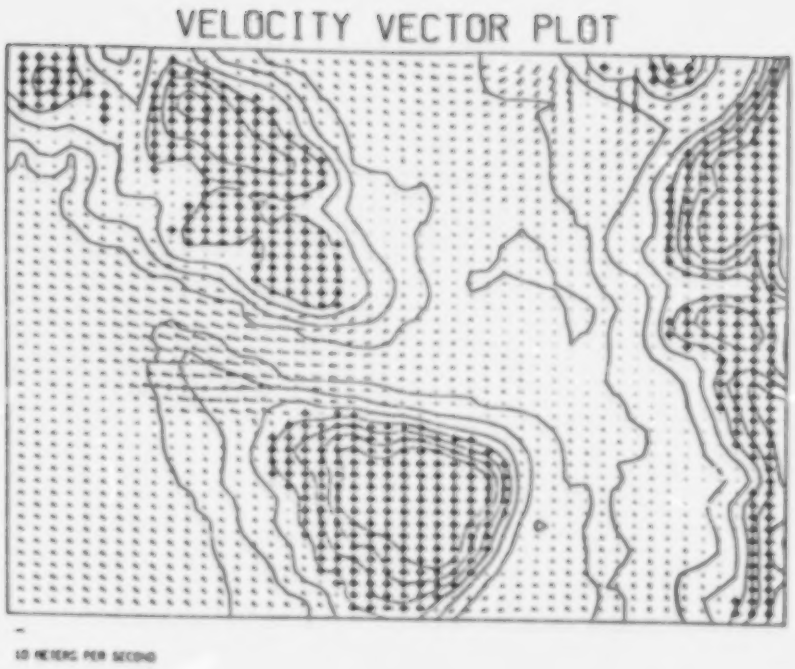


FIGURE 3. East Wind Case: Model Results.

The model was intialized by a geostrophic wind of 4.8 m/s from $144^{0}$ and a low PBL height of 0.5 km as representative of stable conditions throughout the lower troposphere. The major features are: light winds in the central basin, weak easterly flow along the coast, and accelerating easterly flow down gradient through the Strait of Juan de Fuca. Because the flow in all channels is out of the Puget Sound basin, this case could not be run to steady state.

A front that approached the coast at 0000, December 8, 1976 became a cold front of respectable energy as the high retreated far to the south. This case of even isobars and southwesterly geostrophic flow is a good example of the typical situation before the passage of a cold front. One first notices that the flow is channelled by the Olympic Mountains (Figure 4). Winds over Puget Sound are stronger and more southerly than offshore. A region of light winds is evident in the lee of the Olympic Mountains. There is also general steerage of the flow along the axis of Georgia Strait, more than a 90° deflection from the geostrophic wind. The corresponding storm situation of December 8 is simulated by model runs in Figures 5 and 6 for PBL heights of 1800 m and 900 m. Geostrophic wind is 14.7 m/s from 251 deg. The overall wind pattern for the observed PBL height (1800 m) is much smoother than that suggested by observations. The lower height, however, shows the appropriate amount of detail. An eddy as formed at the east end of the Strait of Juan de Fuca near Port Angeles to various degrees in both simulations. The PBL deviations show a gentle rise over the windward side of the mountain with a pronounced lee wave trough on the downwind side of the Olympics and Vancouver Island. With a low inversion height, winds flow through the low point in the mountains of Vancouver Island and spill out over the inland waters.

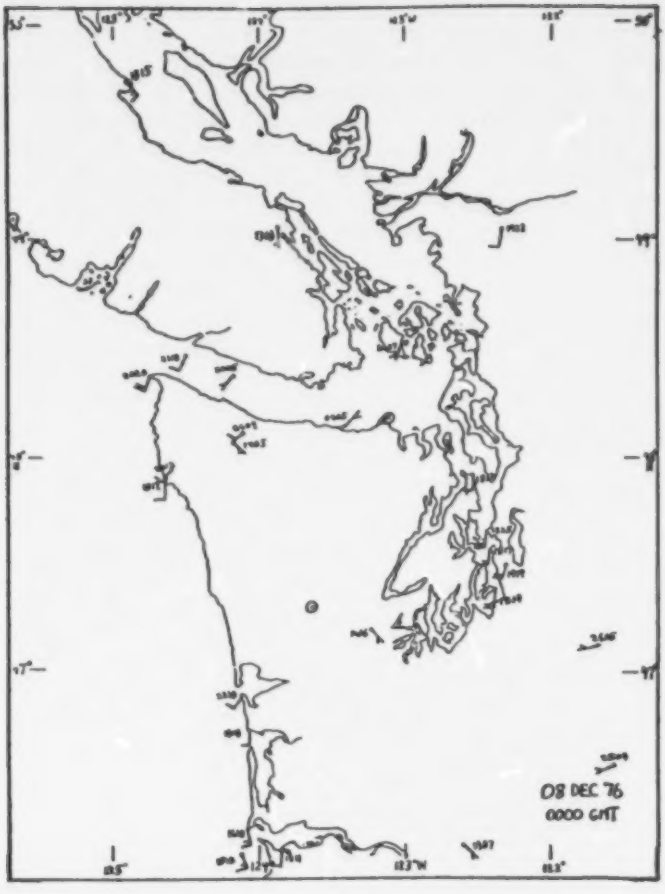


FIGURE 4. Southwest Wind Case: Observations.

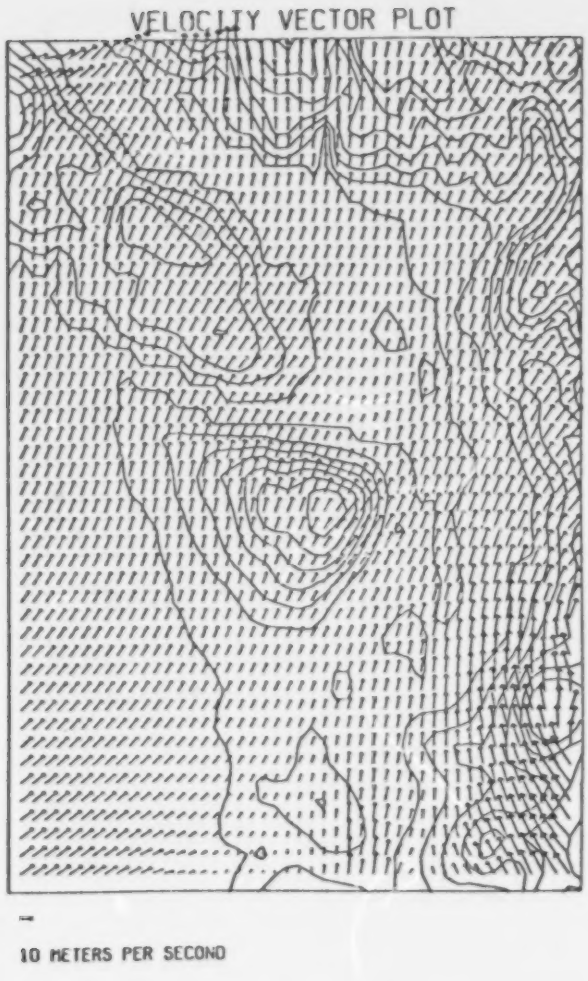


FIGURE 5. Southwest Wind Case: Model Results (h=1800 m).

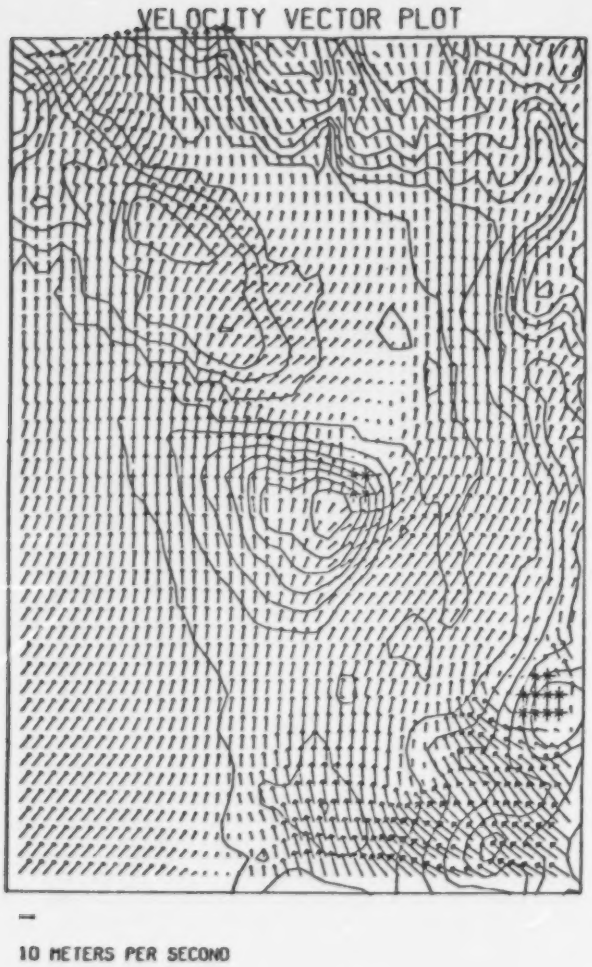


FIGURE 6. Southwest Wind Case: Model Results (h=900 m).

For a day following the December 22 front and a day following the December 8 front a cell of high pressure existed off the coast of Oregon and Northern California which brought strong northwesterly winds through Washington as part of an anticyclonic circulation. Except for temperature effects, this pattern is typical of summertime conditions in the region. Local anemometers (Figure 7) reveal the effect of topography

on a northwesterly geostrophic wind. Strong channelling is indicated in the Strait of Juan de Fuca with variable winds in the lee of the Olympic Mountains. It is interesting that for this case there is a southerly flow in the lower Puget Sound in the lee of the Olympics, but only on the surface.

Figure 8 shows model velocity field for northwest winds. Channelling as indicated in the Strait of Juan de Fuca and especially by the Strait of Georgia. Height deviations are less intense than for the southwest wind case, although the velocity field indicates that the lee wave eddy is still a major feature. A southerly tendency is indicated in the lower Puget Sound where the flow is parallel to the pressure gradient below the ridge crests.

In contrasting the wind and height fields for northwest and southwest winds, northwest winds tend to flow fairly closely to the orientation of the ridge line. Southwest winds funnel flow into Puget Sound, but farther north inertia carries the major volume flux across topographic contours through the low points in the ridge crest. This cross-contour flow induces a major local response in the height field and eddies.

FIGURE 7. Northwest Wind Case: Observations.

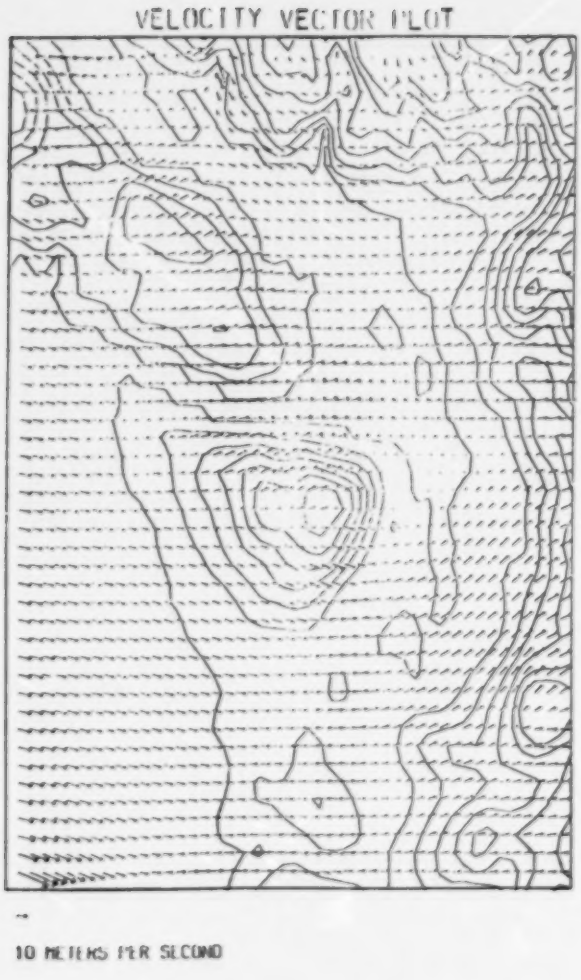


FIGURE 8. Northwest Wind Case: Model Results.

3.2.4. Summary.

The Regional Meteorological Model results presented here are useful to the extent that they serve as a guide to understanding the relationship between the available

measurements at meteorological stations and the surface winds at other points in the study region. For pollutant dispersion modeling this information may be most useful in understanding the errors to be expected in using available measurements to estimate surface winds; considerable effort must be expended by a person knowledgeable in the physics of the atmosphere and the inner workings of the computer implementation of the model to make a single model run. An extension of this work, cataloging the response of the lower atmosphere in the study region to synoptic-scale conditions under several stability conditions, is planned. This will allow the local wind to be computed rapidly by searching for the closest applicable model run(s) currently available in a data base. A further extension of this idea is to interpolate between model results using the model input parameters (initial and boundary conditions) as the independent variables, and the resultant wind fields as the dependent variables. This would allow direct coupling between the Puget Sound pollutant trajectory model and (results of) meteorological model presented here. At present, it is not feasible to couple the two models directly because of the great overhead involved in the meteorological model, its requirement for an expert to run it, and the fact that the two models are currently running on different computer systems.

## 3.3. A Simple Trajectory Model for Puget Sound.

### 3.3.1. Introduction.

The Puget Sound Trajectory model is an operational tool for the prediction of the short term progress of floating masses anywhere within the inland marine waters of Wasington State. The model runs on a DEC PDP-11/55 computer at the NOAA Pacific Marine Environmental Laboratory in Seattle, Washington. It may be accessed remotely via voice-grade telephone lines with suitable terminal equipment and a Bell 103-type modem. The mathematical basis of the model is simple, but the topological and geometrical details have been specified very carefully. These qualities, in combination with a simple and consistent operator interface, make the model a practical tool for dealing with real situations.

### 3.3.2. Brief Mathematical Description.

The model is a computer implementation of a straightforward solution of a simplified form of (1):

$$C_t = -(uC_x + vC_y) + (D_xC_x)_x + (D_yC_y)_y + R \qquad (11)$$

where C is the concentration of the substance, $D_x$ and $D_y$ are eddy diffusion coefficients, u and v are the easterly and northerly velocity components, R is a local rate of generation of the substance, and the remaining x, y, and t subscripts indicate differentiation with respect to the east, north, and time coordinates, respectively. A two-dimensional rectangular coordinate system locally oriented with east and north axes parallel to parallels and meridians on the earth's surface is employed. The curvature of the earth's surface is neglected.

An effective solution can be obtained for pollutant dispersion modeling by following representative particles embedded in the fluid. This (Lagrangian) approach eliminates the need to compute the solution everywhere in order to know the solution in a small area of interest, and it also makes it easier to dynamically alter parameters and to represent boundary conditions realistically. The Lagrangian approach allows the driving variables, surface currents and surface winds, to be cataloged in whatever manner is computationally convenient. The concentration, C, of (11) can be interpreted as an areal particle density in the Lagrangian approach. Estimation of concentration can be made as exact as desired by tracking as many particles as necessary to obtain the required statistical precision. For many distributions, the precision of the concentration estimates is improved in proportion to the square root of the number of particles tracked.

An automated form of the NOS Tidal Current Tables for North America and Asia (NOS, 1975) provides surface currents in the form u(lat,lon,t) and v(lat,lon,t) where u and v are the east and north components of the surface current, lat and lon are the latitude and longitude of a point within western Washington State, and t is a calendar date and time of day. These surface currents are specified for several hundred stations scattered throughout Puget Sound and adjacent waters. An interpolation procedure must be employed in order to obtain surface currents at all points of interest.

The regional meteorological model (Overland, et al, 1978) was developed to compute the effect of terrain and other local processes to yield estimates of local winds over the water in the form $u_W$(lat,lon,t,s) and $v_W$(lat,lon,t,s) where $u_W$ and $v_W$ are the east and north components of the local surface wind, s is a specification of synoptic-scale atmospheric conditions, (perhaps geostrophic wind velocity for the area) and the other parameters are as previously described. The version 1.0 model is not coupled to the regional meteorological model. The computed surface winds must be manually specified to the model via the WIND specification.

Given the means to compute the surface current and surface

wind, the solution procedure then consists of iterations of the form

$$\underline{lat}_p^{n+1} = \underline{lat}_p^n + s_{\underline{lat}} v_p (t^{n+1} - t^n)$$
$$\underline{lon}_p^{n+1} = \underline{lon}_p^n + s_{\underline{lon}} u_p (t^{n+1} - t^n) \qquad (12)$$

where the subscripts denote the identity of the points being followed, and the superscripts denote the iteration number,

$$s_{\underline{lat}} = 0.92 \times 10^{-7}$$
$$s_{\underline{lon}} = 0.92 \times 10^{-7}/\cos(\underline{lat}) \qquad (13)$$

are scale factors, assuming latitude and longitude in degrees,

$$v_p = v(\underline{lat},\underline{lon},t^n) + v_w'(\underline{lat},\underline{lon},t^n,\underline{s}) + v^*$$
$$u_p = u(\underline{lat},\underline{lon},t^n) + u_w'(\underline{lat},\underline{lon},t^n,\underline{s}) + u^* \qquad (14)$$

are the surface velocity components after allowing for the effects of wind where

$$v_w' = a_w(t_2 u_w(\underline{lat},\underline{lon},t,\underline{s}) + t_1 v_w(\underline{lat},\underline{lon},t,\underline{s}))$$
$$u_w' = a_w(t_1 u_w(\underline{lat},\underline{lon},t,\underline{s}) - t_2 v_w(\underline{lat},\underline{lon},t,\underline{s})) \qquad (15)$$

where $a_w$ is a coefficient that relates the wind speed to its effectiveness in moving the floating substance (typically a value between 0.01 and 0.10 is used) and $t_1 = \cos(r_w)$ and $t_2 = \sin(r_w)$ where $r_w$ is the angle between the measured or estimated surface wind and its effective direction at the air-water interface, and

$$v^* = \frac{(D_y(t^{n+1} - t^n))^{-\frac{1}{2}}}{t^{n+1} - t^n} R_0^1$$
$$u^* = \frac{(D_x(t^{n+1} - t^n))^{-\frac{1}{2}}}{t^{n+1} - t^n} R_0^1 \qquad (16)$$

which account for the effects of turbulent diffusion parameterized by eddy diffusivities $D_y$ and $D_x$ (Csanady, 1973), and $R_a^b$ is a pseudorandom number uniformly distributed over the interval (a,b). Up to 64 particles may be tracked with the version 1.0 model.

The entire water-land boundary is treated as a trap for particles that come in contact with it. Once a particle is tracked to within the model resolution of land (about 40 m) it becomes trapped and will not move again. Particles that move outside the particular area being displayed on the graphic

device are not lost to the simulation and may reappear at a later time. Particles that travel outside Juan de Fuca Strait to the west or Georgia Strait to the north will become lost to the computation, because there is no current information outside the Puget Sound region.

### 3.3.3. Data Sources.

The model requires surface current velocities, surface wind velocities, and a map to compute the water predicate.

#### 3.3.3.1. Surface Currents.

Conceptually, at least, surface currents could be derived from any available source. In practice, it must be possible to compute a single surface current velocity in no more than a few milliseconds if the model is to remain interactive. This leads to the use of the most rapid interpolation possible: nearest station assignment by Euclidean metric.

#### 3.3.3.2. Surface Winds.

As in the case of surface currents, surface winds must be computed in several milliseconds time if the model is to be interactive. This requirement precludes any direct connection between the Regional Meteorological Model and the PSTM except by building a data base of Regional Meteorological Model results. This has not yet been accomplished, so results of a surface wind computation must be manually entered into the PSTM via the WIND specification.

3.3.3.3. Geometry. One of the more difficult problems is the apparently simple task of computing whether a point is on land or water. The method used for the PSTM was to

1. perform geometric corrections to two cloud-free LANDSAT images of western Washington, and

2. build a bit-map where the corresponding bit was set if the pixel (image resolution element) in the scene's band 7 (near-infrared) had a value less than 5 (this value was determined by examining the radiance values for a number of known land and water areas in the images).

This bitmap was hand-edited to remove objects in the water that were not land such as bridges and ships. The resolution of the bitmap is about 100 m.

### 3.3.4. User Interface.

The person actually trying to use the PSTM to investigate real situations is able to control its operation through the user interface. An extended explanation of how this may be accomplished is contained in Appendix I. The user interface was designed to allow a user to remember as little as possible of the details of model operation. Typing an incorrect command, for example, causes a list of all possible commands to be displayed. Typing a correct command in an improper form causes a prototype correct form to be displayed. All commands have the same general form. All similar types of information are entered in the same format. Commands may be entered in any order. Finally, the user interface is fully modular so that new or modified commands may be easily incorporated at any time.

### 3.3.5. Comparison of PSTM Results with Observations.

There has been no systematic field verification carried out during FY 1977. Some informal comparisons with drogue studies during early FY 1978 showed general agreement.

## 4. SUMMARY.

A simple, modular, single-phase trajectory model has been developed for floating pollutants in the marine waters of western Washington State. A simple method is used to compute surface currents from an existing data base. Surface wind estimates must be estimated or manually transferred from a regional meteorological model. The model has been operational since October, 1977, but has not been verified by comparison with field observations.

There are a number of areas in which the model could be improved or extended, including (in approximate order of importance):

1. completion of the regional meteorological model data base

2. use of preassignment and the $d_w$ metric in surface current interpolation

3. improved parameterization of wind effect

4. inclusion of special behavior modules for specific substances (for example, spreading of oil)

5. extension to K>1

6. implementation of $C^k$ estimation

7. implementation of "reverse time" for sensitivity studies

8. improvement of current data base

9. calculation of currents from a hydrodynamic model.

A continuation of the trajectory modeling work was extended into FY 1978 by the Numerical Studies Group at PMEL. Part of the FY 1978 program is to incorporate the meteorological model results into the trajectory model. More details of the planned work are in the proposal to the Puget Sound MESA Project for FY 1978.

## 5. REFERENCES.


Csanady, 1973. Turbulent Diffusion in the Environment. D. Reidel, Boston.

Danard, 1975. A Numerical Model for Surface Winds in Juan de Fuca, Haro, and Georgia Straits. Report to Atmospheric Environment Services, Downsview, Ontario.

Kernighan, 1975. RATFOR-A Preprocessor for a Rational Fortran, Software Practice and Experience, October.

Lavoie, 1972. A Mesoscale Numerical Model of Lake-Effect Storms. J. Atmos. Sci 29, 1025-1040.

Lavoie, 1974. A Numerical Model of Tradewind Weather on Oahu. Mon. Wea. Rev. 102, 630-637.

Nilsson, 1971. Problem Solving Methods in Artificial Intelligence. McGraw-Hill, New York, 57-71.

NOS, 1975. Tidal Current Predictions for the Pacific Coast of North America and Asia -1976.

Nuler, 1975. Deepening of the Wind-Mixed Layer. J. Mar. Res. 33, 405-422.

Mahrt and Lenschow, 1976. Growth Dynamics of the Convectively Mixed Layer. J. Atmos. Sci. 33, 41-45.

Maunder, 1970. Algebraic Topology. Van Nostrand Reinhold, London, 19-20.

Ogura and Phillips, 1962. Scale Analysis of Deep and Shallow Convection in the Atmosphere. J. Atmos. Sci. 19, 173-179.

Overland, et al, 1978. A Regional Surface Wind Model for Mountainous Coastal Areas. PMEL, ERL, NOAA Tech. Rept. (in preparation).

Zenman and Tennekes, 1977. Parameterization of the Turbulent Energy Budget at the Top of the Daytime Atmospheric Boundary Layer. J. Atmos. Sci. 34, 111-123.

Zilitinkevich, 1975. Comments on the Paper by H. Tennekes. J. Atmos. Sci. 32, 991-992.

# APPENDIX I. Puget Sound Trajectory Model User's Guide

NOTE. The material in this Appendix duplicates some material in section 3 of this report. This Appendix is designed to be a self-contained manual for use of the Puget Sound Trajectory Model version 1.0.

## SUMMARY.

The Puget Sound Trajectory model is an operational tool for the prediction of the short term progress of floating masses anywhere within the inland marine waters of Wasington State. The model runs on a DEC PDP-11/55 computer at the NOAA Pacific Marine Environmental Laboratory in Seattle, Washington. It may be accessed remotely via voice-grade telephone lines with suitable terminal equipment and a Bell-103-type modem. The mathematical basis of the model is simple, but the topological and geometrical details have been specified very carefully. These qualities, in combination with a simple and consistent operator interface make the model a practical tool for dealing with real situations.

## THE MODEL.

The model is a computer implementation of a straightforward solution of a simplified distribution of variables (conservation of mass) equation for an incompressible fluid carrying a single pollutant substance whose physical behavior is indistinguishable from that of the fluid itself. An appropriate mass conservation principle may be expressed in an Eulerian frame of reference as

$$C_t = -(uC_x + vC_y) + (D_xC_x)_x + (D_yC_y)_y + R \qquad (I\text{-}1)$$

where C is the concentration of the substance, $D_x$ and $D_y$ are eddy diffusion coefficients, u and v are the easterly and northerly velocity components, R is a local rate of generation of the substance, and the remaining x, y, and t subscripts indicate differentiation with respect to the east, north, and time coordinates, respectively. A two-dimensional rectangular coordinate system locally oriented with east and north axes parallel to parallels and meridians on the earth's surface is employed. The curvature of the earth's surface is neglected.

An effective solution can be obtained for pollutant dispersion modeling by following representative particles embedded in the fluid. This (Lagrangian) approach eliminates the need to compute the solution everywhere in order to know the solution in a small area of interest, and it also makes it easier to dynamically alter parameters and to represent boundary conditions realistically. The Lagrangian approach allows the driving variables, surface currents and surface winds, to be cataloged in whatever manner is computationally convenient. The concentration, C, of (I-1) can be interpreted as an areal particle density in the Lagrangian approach. Estimation of concentration can be made as exact as desired by tracking as many particles as necessary to obtain the required

statistical precision. For many distributions, the precision of the concentration estimates is improved in proportion to the square root of the number of particles tracked.

An automated form of the NOS Tidal Current Tables for North America and Asia (NOS, 1975) provides surface currents in the form $u(\underline{lat},\underline{lon},t)$ and $v(\underline{lat},\underline{lon},t)$ where u and v are the east and north components of the surface current, $\underline{lat}$ and $\underline{lon}$ are the latitude and longitude of a point within western Washington State, and t is a calendar date and time of day. These surface currents are specified for several hundred stations scattered throughout Puget Sound and adjacent waters. An interpolation procedure must be employed in order to obtain surface currents at all points of interest. Several procedures are discussed in section 3.1.2.; the method used in the version 1.0 model is assignment by Euclidean metric.

A regional meteorological model (Overland, et al, 1978) has been developed to compute the effect of terrain and other local processes to yield estimates of local winds over the water in the form $u_w(\underline{lat},\underline{lon},t,\underline{s})$ and $v_w(\underline{lat},\underline{lon},t,\underline{s})$ where $u_w$ and $v_w$ are the east and north components of the local surface wind, $\underline{s}$ is a specification of synoptic-scale atmospheric conditions, (perhaps geostrophic wind velocity for the area) and the other parameters are as previously described. The version 1.0 model is not coupled to the regional meteorological model. The computed surface winds must be manually specified to the model via the WIND specification.

Given the means to compute the surface current and surface wind, the solution procedure then consists of iterations of the form

$$\begin{aligned} \underline{lat}_p^{n+1} &= \underline{lat}_p^n + s_{\underline{lat}} v_p (t^{n+1} - t^n) \\ \underline{lon}_p^{n+1} &= \underline{lon}_p^n + s_{\underline{lon}} u_p (t^{n+1} - t^n) \end{aligned} \qquad \text{(I-2)}$$

where the subscripts denote the identity of the points being followed, and the superscripts denote the iteration number,

$$\begin{aligned} s_{\underline{lat}} &= 0.92 \times 10^{-7} \\ s_{\underline{lon}} &= 0.92 \times 10^{-7} / \cos(\underline{lat}) \end{aligned} \qquad \text{(I-3)}$$

are scale factors, assuming latitude and longitude in degrees,

$$v_p = v(\underline{lat},\underline{lon},t^n) + v'_w(\underline{lat},\underline{lon},t^n,\underline{s}) + v^*$$
$$u_p = u(\underline{lat},\underline{lon},t^n) + u'_w(\underline{lat},\underline{lon},t^n,\underline{s}) + u^* \qquad \text{(I-4)}$$

are the surface velocity components after allowing for the effects of wind where

$$v'_w = a_w(t_2 u_w(\underline{lat},\underline{lon},t,\underline{s}) + t_1 v_w(\underline{lat},\underline{lon},t,\underline{s}))$$
$$u'_w = a_w(t_1 u_w(\underline{lat},\underline{lon},t,\underline{s}) - t_2 v_w(\underline{lat},\underline{lon},t,\underline{s})) \qquad \text{(I-5)}$$

where $a_w$ is a coefficient that relates the wind speed to its effectiveness in moving the floating substance (typically a value between 0.01 and 0.10 is used) and $t_1 = \cos(r_w)$ and $t_2 = \sin(r_w)$ where $r_w$ is the angle between the measured or estimated surface wind and its effective direction at the air-water interface, and

$$v^* = \frac{(D_y(t^{n+1} - t^n))^{-\frac{1}{2}}}{t^{n+1} - t^n} R_0^1$$
$$u^* = \frac{(D_x(t^{n+1} - t^n))^{-\frac{1}{2}}}{t^{n+1} - t^n} R_0^1 \qquad \text{(I-6)}$$

which account for the effects of turbulent diffusion parameterized by eddy diffusivities $D_y$ and $D_x$ (Csanady, 1973), and $R_a^b$ is a pseudorandom number uniformly distributed over the interval (a,b). $D_x = D_y = 10^6$ cm$^2$/sec in the version 1.0 model. Up to 64 particles may be tracked with the version 1.0 model.

The entire water-land boundary is treated as a trap for particles that come in contact with it. Once a particle is tracked to within the model resolution of land (about 40m) it becomes trapped and will not move again. Particles that move outside to particular area being displayed on the graphic device are not lost to the simulation and may reappear at a later time. Particles that travel outside Juan de Fuca Strait to the west or Georgia Strait to the north will become lost to the computation, because there is no current information outside the Puget Sound region.

## OPERATOR INTERFACE.

Access to the model may be gained by dialing from a computer terminal capable of operating at 300(1200)baud using a Bell 103(212A)-type modem. The operating system will respond with (note that all computer responses are underlined)

PDS>

the operator types "LOGIN OIL"

PDS>LOGIN OIL<CR>

PASSWORD?SPILL<CR>

the operating system will respond with a message and

PDS>

at which point the operator types "OIL" and the system will respond

PDS>OIL

OIL>

indicating that the model-operator interface is active.

### Specifications and Directives.

The version 1.0 model is controlled by two types of commands. The first type are specifications. Specifications set parameters within the model but no simulation actually occurs. When a directive (RUN or STATUS) is issued by the operator, the model takes some action, and the operator will receive some sort of report. What follows is a list of all the commands available in the version 1.0 model and a brief description of the use of each.

TOP nn:nn:nna

where n is a digit and a is "n" or"s". The TOP specification controls the top (north) limit of the area to be modelled. For example,

OIL>TOP 49:00:00N

would specify that latitude 49 degrees, 0 minutes, 0 seconds north would be the top of the modelled region. The default value is 49:20:00N.

BOTTOM nn:nn:nna

where n is a digit and a is "N" or "S". The BOTTOM specification controls the bottom (south) limit of the area to be modelled. For example,

OIL>BOTTOM 48:30:00N

would specify that latitude 48 degrees, 30 minutes, 0 seconds north would be the bottom of the modelled region. The default value is 47:02:00N.

LEFT nnn:nn:nna

where n is a digit and a is "E" or "W". The LEFT specification controls the left (west) limit of the area to modelled. For example,

OIL>LEFT 122:00:00W

would specify that longitude 122 degrees, 0 minutes, 0 degrees west would be the left edge of the modelled region. The default value is 124:44:00W.

RIGHT nnn:nn:nna

where n is a digit and a is "E" or "W". The RIGHT specification controls the right (east) limit of the area to be modelled. For example,

OIL>RIGHT 121:45:00W

would specify that longitude 121 degrees, 45 minutes, 0 seconds west would be the right edge of the modelled region. The default value is 122:12:00W.

POINT pointname latitude longitude

where pointname is an alphanumeric identifier for a distinguished point whose geographic position (latitude and longitude) is specified as in the TOP and LEFT spefications. For example,

OIL>POINT TANKER 48:27:12N 121:36:58W

defines TANKER as the name of a distinguished point at latitude 48 degrees, 27 minutes, 12 seconds north, and longitude 121 degrees, 36 minutes, 58 seconds west. The identifier TANKER has no special meaning to the model, except that it specifies a particular location. There are no points defined initially.

SOURCE pointname $u_{source}$ $v_{source}$ $r_{source}$

where pointname is an identifier previously defined by a POINT specification, $u_{source}$ is the east velocity component of the source in cm/sec, $v_{source}$ is the north velocity component of the source in cm/sec, and $r_{source}$ is the rate of production of traceable floating elementss per hour. For example,

OIL>SOURCE TANKER 0 0 10

indicates that there is a source of 10 traceable floating elements/hr at a stationary location named "TANKER" defined previously with a POINT specification. There are no sources defined initially.

SPILL amount $point_1$ $point_2$ ... $point_n$

where amount is the number of traceable floating elements in the polygon defined by the vertices $point_1$ $point_2$ ... $point_n$. The SPILL specification defines areas of traceable floating elements. For example,

OIL>SPILL 25 P1 P2 P3 TANKER

would specify 25 traceable floating particles in the quadrilateral P1-P2-P3-TANKER. SPILL is used to represent pre-existing areas of floating material.

START dd-aaa-yy hh:mm:ss

where yy is the last 2 digits of a year, aaa is a month abbreviation (JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC), dd is a 2-digit day specification, hh is a 2-digit hour specification (PST), mm is a 2-digit minutes specification, and ss is a 2-digit second specification. The START specification controls the date and time of the beginning of a model run. For example,

OIL>START 15-SEP-77 12:01:00

The default start time is 00:00:00 01-JAN-76.

STOP dd-aaa-yy hh:mm:ss

where the parameters are the same as required in the START specification. The STOP specification controls the date and time for the end of a model run. For example,

OIL>STOP 16-SEP-77 12:00:00

would specifiy a model stop time. The default stop time is 00:00:00 01-JAN-76.

TIMESTEP mm

where mm is the timestep size in minutes. The TIMESTEP specification controls the amount of time between successive frames of model output. The internal step size may not be larger than the specified interval, and a smaller increment may actually be used for computations. The operational user need not be aware of this detail. For example,

OIL>TIMESTEP 15

would specify a 15 minute (modelled time) display interval. The default timestep is 60 minutes.

DEVICE aaa...

where aaa.... is an alphanumeric device or a file specification valid on the system where the model is run. The DEVICE specification lets the model tailor its output to the device in use. For example,

OIL>DEVICE TEKTRONIX-4012

would cause any output generated to be compatible with a Tektronix model 4012 display terminal. The default device is a TEKTRONIX-4012.

WIND speed direction percent angle

where speed is the wind speed in knots, direction is in degree clockwise from true north, percent is $100a_w$ (Equations I-4) and angle is $r_w$ (Equations I-4). For example,

OIL>WIND 15 300 5 0

specifies a 15 knot wind from 300 degrees with 5 percent effect and no rotation. The default value for wind is zero.

BACKGROUND option

where the background consists of a dot representation of the coastline and need not be drawn every timestep. Options available are YES, NO and ONCE. With YES a background will be drawn every timestep. With NO the background is never drawn. With ONCE the background is drawn once. The default background option is ONCE.

STATUS

will print out a synopsis of all important model parameters. STATUS may be used at any time.

RUN mode

where mode is "TABLE", "CHART",or "SPILL". The TABLE mode produces a table of surface drift velocity components at all distinguished points. The chart mode produces vector charts of surface drift velocity components, at a number of points covering the modelled area (similar to NOS tidal current charts), and the SPILL mode produces a sequence of charts depicting the location and concentration of tracable floating elements. RUN and STATUS are the only directives in the version 1.0 model.

Figure I-1 is a STATUS report for a typical model run. Four distinguished points have been named in the Rosario Strait area. A twenty-four hour model run has been specified.

```
TOP = 48:45:00N
BOTTOM = 48:30:00N
LEFT = 122:51:59W
RIGHT = 122:29:59W
START = 00:00:00 01-NOV-77
STOP = 02:00:00 02-NOV-77
TIMESTEP = 60
DEVICE = TEKTRONIX-4012
UWIND,VWIND IN TENTHS 0.0
BACKGROUND = YES

LAWR            48:42:30N-122:42:45W    0.0 2
VITI            48:37:50N-122:38:10W    0.0 2
BELLC           48:33:10N-122:40:00W    0.0 2
ROSE            48:34:40N-122:45:40W    0.0 2

OIL>
```

FIGURE I-1. Trajectory model status report.

Figure I-2 is the current report generated by RUN TABLE. The current vectors are listed by direction in degrees from true north, and in speed in tenths of a knot for each distinguished point.

```
RUN TABLE CURRENTS ARE IN TENTHS OF KNOTS
                          LAWR          VITI          BELLC          ROSE
00:00:00 01-NOV-77     145  19       110  9       -174 25       -169 33
01:00:00 01-NOV-77     145  17       110  8       -174 18       -169 29
02:00:00 01-NOV-77     145  13       110  6       -174  8       -169 21
03:00:00 01-NOV-77     145   7       110  3         44  2       -169  9
04:00:00 01-NOV-77     145   0       110  0         45 10         10  2
05:00:00 01-NOV-77     -14   8       -55  0         44 16         10 13
06:00:00 01-NOV-77     -14  18       -55  1         44 18         10 21
07:00:00 01-NOV-77     -14  20       -55  1         44 18         10 23
08:00:00 01-NOV-77     -14  19       -55  1         45 11         10 21
09:00:00 01-NOV-77     -14  14       -55  1         45  4         10 14
10:00:00 01-NOV-77     -14   7       -55  0       -174 2         10  6
11:00:00 01-NOV-77     145   0       -55  0       -174 8       -169 2
12:00:00 01-NOV-77     145   4       110  2       -174 11      -169 9
13:00:00 01-NOV-77     145   7       110  3       -174 11      -169 13
14:00:00 01-NOV-77     145   7       110  4       -174 9       -169 13
15:00:00 01-NOV-77     145   6       110  3       -174 6       -169 11
16:00:00 01-NOV-77     145   4       110  2       -174 2       -169 7
17:00:00 01-NOV-77     145   2       110  1       -174 0       -169 3
18:00:00 01-NOV-77     145   0       110  0       -174 1       -169 1
19:00:00 01-NOV-77     145   0       110  0       -174 5       -169 1
20:00:00 01-NOV-77     145   2       110  1       -174 10      -169 5
21:00:00 01-NOV-77     145   5       110  2       -174 16      -169 12
22:00:00 01-NOV-77     145  10       110  4       -174 21      -169 19
23:00:00 01-NOV-77     145  13       110  6       -174 24      -169 25
00:00:00 02-NOV-77     145  16       110  8       -174 24      -169 28

OIL>
```

FIGURE I-2. Current table report.

Figure I-3 shows one of the current vector diagrams produced by RUN CHART. The size of the arrows is proportional to the current speed. Twenty-five charts were generated by the parameters shown in Figure I-1.

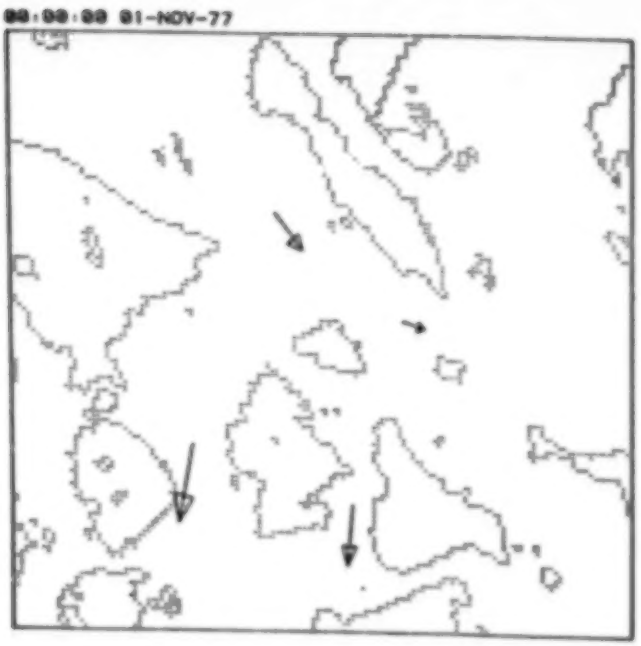


FIGURE I-3. Current vector diagrams.

Figure I-4 shows the first four displays of floating element locations produced by RUN SPILL for the parameters given in Figure I-1. A superimposition of all 25 diagrams as shown in Figure I-5. Figure I-5 was obtained by specifying BACKGROUND ONCE.

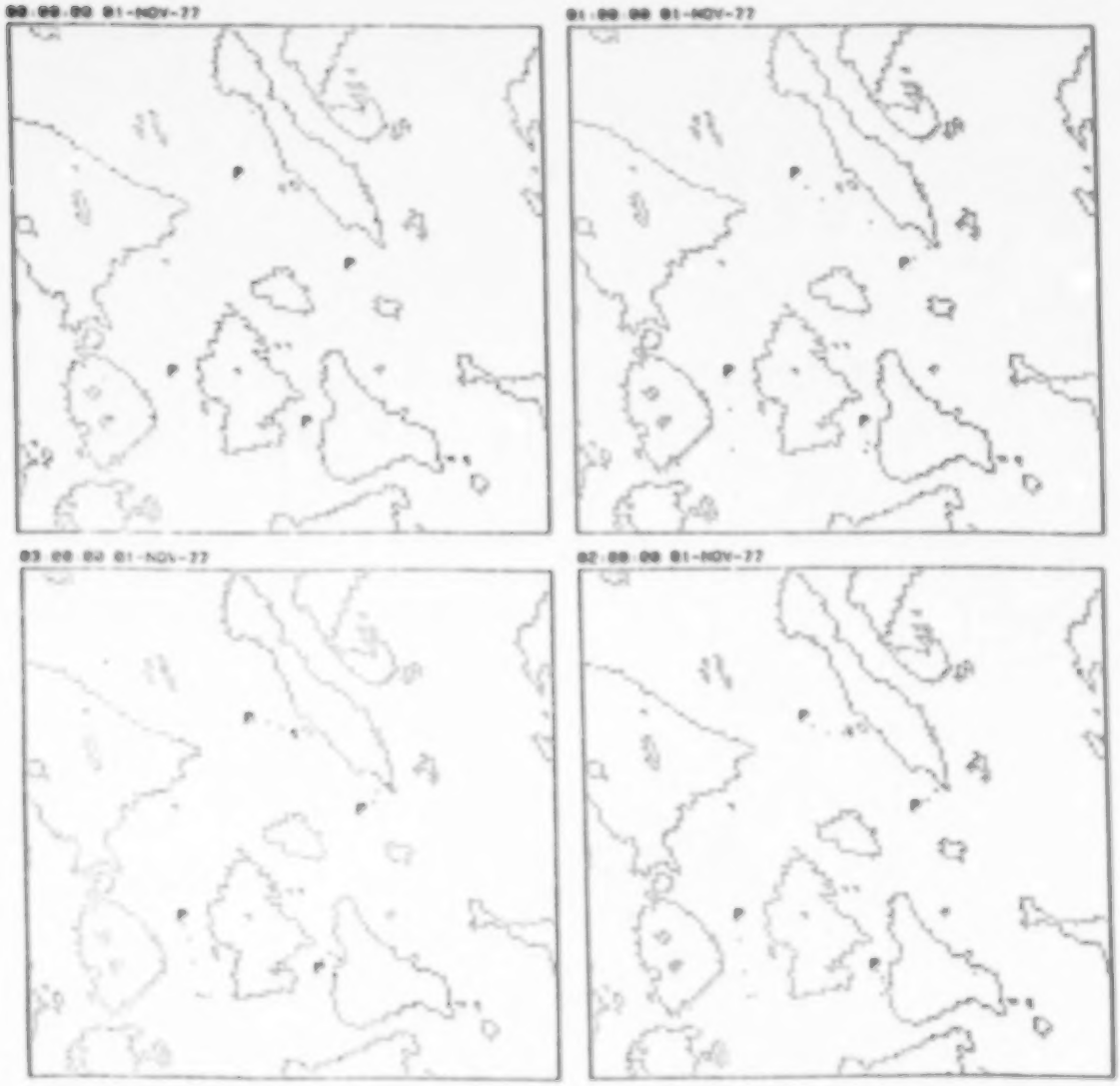


FIGURE I-4. Spill trajectory plots (clockwise from upper left).

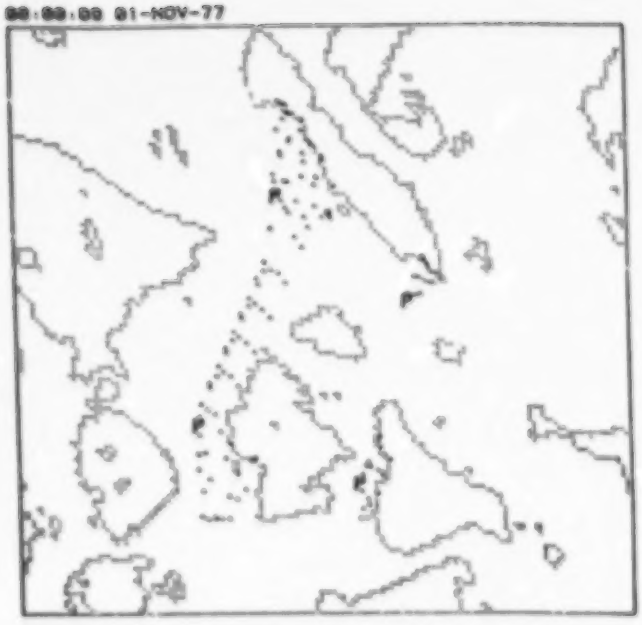


FIGURE I-5. Superimposed trajectory plot.

☆U.S. GOVERNMENT PRINTING OFFICE: 1978-0-779-137/43